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A THESIS
SUBMITTED TO THE FACULTY
OF
PURDUE UNIVERSITY
BY
[illegible] [illegible] [illegible]
IN PARTIAL FULFILLMENT
OF THE
REQUIREMENTS FOR THE DEGREE
OF
MASTER OF SCIENCE
IN
[illegible] [illegible]
June, [illegible]

EFFECT OF LEVER SIZE UPON TIME REQUIRED TO OPERATE

A Thesis

Submitted to the Faculty

of

Purdue University

by

Antonio Augusto Abreu Caminada

In Partial Fulfillment

of the

Requirements for the Degree

of

Master of Science

in

Industrial Engineering

June, 1952

ACKNOWLEDGMENTS

The author wishes to express his gratitude to Professor H. T. Amrine, to Professor I. W. Burr and to Professor P. E. Irick for their guidance and assistance, and to Professor E. J. McCormick and Professor W. J. Richardson for their assistance.

The author is also greatly indebted to those who helped him as subjects and whose names follow: E. G. Lindquist, J. O. House, R. J. Wimmert, C. Kromp, P. D. Viana, R. H. Doolittle, J. Crim, G. A. Grabowsky, H. T. Fichman and O. Bromberg.

The author expresses again many thanks to his friend P. D. Viana for his valuable help.

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ABSTRACT

This experiment deals with the determination of the effect of the size of a lever upon the time required to operate it.

The equipment was built to provide a constant torsional resistance which was to be overcome by an operator using a lever that moved between two mechanical stops.

A kymograph was used to register the time and provided an effective means to analyze the operator performance in regard to time used to operate, as well as to pace maintained and correct operation.

Ten subjects were used; they were college students and varied considerably in age and physical characteristics.

Twenty-five combinations of five levers of different sizes and five different torques were used. All the operators were instructed to operate the lever at the maximum possible speed that they thought they would be able to maintain during eight seconds.

The position of the operator relative to the equipment was kept constant and such that his elbow was 16.4 inches above the shaft around which the lever rotated (this length corresponds to the average lever size) and the forearm length away from it.

It was concluded that, under the conditions of the

experiment and for the group of operators who performed the tests,

(a) when the torque increases and the lever size is kept constant, the time required to operate increases closely proportional to the torque.

(b) The time required to operate is closely proportional to the distance that the hand has to travel.

(c) The path that the hand has to travel is, probably, the predominant factor determining the time for operation.

(d) The 10-inch lever requires the minimum time for operation and the 25-inch lever requires the maximum time for operation.

INTRODUCTION AND PURPOSE

When one examines a modern machine tool, generally he is led to the conclusion that it has achieved a relatively high degree of perfection in regard to the performance of its mechanisms. However, if further consideration is given to the analysis of its adequacy in regard to its use by the human element, it is not always possible to arrive at a similar conclusion. Only by complete integration of machine and operator is it possible to get complete efficiency in machine tool operation.

One of the elements which contributes to efficient operation of machine tools is adequate controls. The determination of adequate controls for different situations which exist in practice is an important problem that has not been given much consideration. Therefore, in developing a machine the design engineer probably will find inadequate information to use in order to meet the needs of the required ease of operation.

The experiment which is described in this paper originated from the desire to give a small contribution to the advancement of the knowledge of the immense field of application of handwheels, cranks, levers and knobs.

The author chose levers as his problem and aimed to determine that lever size which requires the least time to operate when used to overcome a constant torsional resistance.

A SURVEY OF THE LITERATURE

The literature available dealing with research on the field of levers is not very extensive.

Barnes[1] discusses the subject of levers, crossbars and handwheels in regard to their position in machine tools and gives results of related studies.

Kühne[2] presents a discussion of studies dealing with determination of the effectiveness of levers, crossbars and handwheels under several different conditions.

Chapanis, Garner and Morgan[3] present a general study, as well as a group of experimental results, of the subject of controls of airplanes. This study is primarily devoted to the analysis of control forces. These authors also discuss other kinds of controls, such as handwheels and cranks, as well as several types of movements which are of interest.

---

1. Barnes, R. M., "Principles of Motion Economy as Related to the Design of Tools and Equipment", Motion and Time Study, John Wiley and Sons, Inc., New York, 1951, Chap. 17.

2. Kühne, W. P., "Studies on the Optimum Force Exerted on Machine Controls", Industrielle Psychotechnik, June, 1927, Vol. III, No. 6, pp. 167-172.

3. Chapanis, A., Garner, W. R. and Morgan, C. T., "Controls for Human Use", How We Make Movements, Applied Experimental Psychology -- Human Factors in Engineering Design, John Wiley & Sons, Inc., New York, 1949, pp. 297-330; 264-297.

McFarland[4] discusses results of studies of control forces related to the performance of the pilot of an airplane who operates sticks or wheels; he also analyzes the problem of maxima, minima and desirable forces.

Davis[5] gives the results of research in the field of handwheels, cranks and crossbars and discusses related problems.

The existence of so limited information on the subject of lever operation seems to indicate the need for further study in this field and makes research dealing with it worthwhile to consider.

---

4. McFarland, R. A., Human Factors in Air Transport Design, McGraw-Hill Book Co., New York, 1946, pp. 384-388, 426-427, 478.

5. Davis, L. E., "Manual Controls", Machine Design, September, 1949, Vol. 21, pp.127-130.

EXPERIMENTAL PROCEDURE

While designing the experimental procedure, the author kept always in mind his intention of setting up the experiment in a way that resembled a practical situation and such that, if any useful results were obtained, they would represent an answer to a question which might arise in practice.

EQUIPMENT

The equipment was built to provide a means of applying a constant torsional resistance to a rotating shaft. This was to be turned at a certain angle (90°) with the use of a lever attached to one of its ends (Figure 1).

Several ways of getting a torque to be overcome by the action of a lever were considered, but they were ruled out as inadequate because they did not meet one of the most important requirements of the experiment, that is, to provide a constant torsional resistance. For this reason, the author decided to use a belt and drum arrangement (Figure 1). This provided a frictional torque which seemed to meet the requirement. Later, when the equipment was built and tested, this assumption was confirmed. The arrangement chosen not only allowed the torque to be kept constant but also permitted an easy change of torque for successive runs by simply varying the spring tension of each scale (Figure 1).

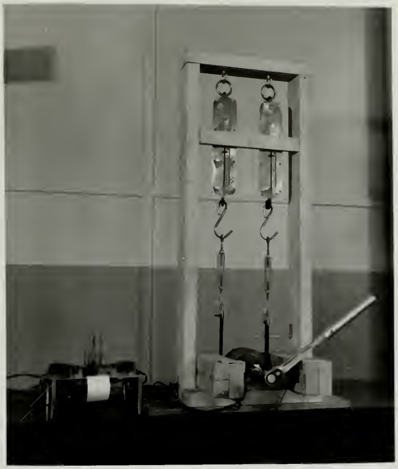

Figure 1

The Equipment used in the Experiment

The choice of the range of torques to be used was based on two main considerations:

(a) using torques usually found in practice;

(b) the need of providing a reasonable variation among the torques in order to have a detectable difference in the related times.

In order to meet the first consideration, the author consulted different sources[1] and finally concluded that, in general, the torques found in practice are not excessive and that a maximum of 150 inch-pounds could be used. The difference among the torques was established as 30 inch-pounds. However, for convenience of use of the equipment, the following values were finally adopted: 28, 59, 89, 112 and 145 inch-pounds.

In choosing the lengths of levers to be used in the experiment, practical sources of information were also considered. The author examined the levers on the machine tools in the Michael Golden Laboratory of Purdue University; he also checked catalogues of tools[2]. Since the sizes of levers found on both machine tools and hand tools range from 4 inches to about 45 inches (the majority being in the range of 10 to 25

[1] Jergens Tool Specialty Co., Catalogue of Jigs and Fixtures Component Parts.
Siewek Tool Division of Domestic Industries, Inc., Clamps, Details and Fixtures Locks.
Chapanis, A., and others (Op. Cit.), pp. 320-321.
Davis, L. E. (Loc. Cit.).
Handbook of Human Engineering Data - Office of Naval Research - Technical Report SDC 199-1-1, Part VI, Chap. II, Sec. III.

[2] Armstrong Bros. Tools Co., Armstrong Tools Catalogue; Siewek Tool Div. of Domestic Industries, Inc. (Op. Cit.).

inches), the following lengths were adopted: 10, 12, 15, 20 and 25 inches (Figure 2). The five levers used in the experiment were obtained by using an ordinary commercial type of ratchet wrench (Figure 2) and five extensions made of steel pipe. The use of the ratchet wrench was adopted to permit the use of a frictional torque without the inconveniences which would otherwise occur due to the periodic reversal of the motion of the lever during the test (this motion will be described in the Procedure). The inconveniences mentioned above refer to the slack of the belt and consequent change of the torque occurring during each reversal of the motion.

To measure the time involved in the operation, the kymograph[1] (Figure 1) was used. The time recorded was that required to move between two mechanical stops during several cycles. It was important that some means exist to check if the operator actually touched both stops with the lever; otherwise, the operation was incorrect and the time measured wrong. The pencil of the kymograph was actuated by a solenoid which was energized when the lever touched the stop and simultaneously closed a switch. The speed of the paper of the kymograph was equal to 9.031 inches per second.

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[1] For a description of the kymograph, see -- Barnes, R. M., "A Study of Hand Motion Using the Principle of the Kymograph", University of Iowa Studies in Engineering, Bulletin 6.

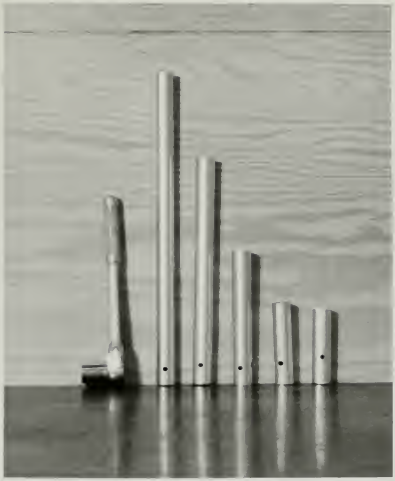

Figure 2

The Levers used in the Experiment

PROCEDURE

Ten male college students were used as subjects. Their physical statistics are presented in Table 1.

The position of the operator relative to the equipment was given much consideration. In general, 36 inches is the height most commonly used for control devices on standard machine tools[1]. Also, the performance of an operator facing equipment has been found much better than that obtained when he is at right angles to the equipment[2]. In addition, it has been determined that motions involving mainly the elbow joint tend to give higher average velocities than those involving the shoulder joint, when the paths are similar[3]. Certainly, the ideal situation would have been to have the muscular pattern involved in each run exactly the same, by varying the position of the operator relative to the equipment. However, to do this would make the experiment much more involved. Weighing all these factors, a position was selected which was kept constant during all the runs for an operator. The position was such that the operator stood

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1. Davis, L. E., (Op. Cit.).

2. Davis, L. E. (Ibid.)
Barnes, R. M., Mundel, M. E., "A Study of Motion Paths Involving Different Degrees of Change Direction", University of Iowa Studies in Engineering, Bulletin No. 12, p. 17.

3. University of Iowa Studies in Engineering (Ibid.).

Table 1

PHYSICAL STATISTICS OF THE SUBJECTS

No.		Age (yr.)	Height (ft-in)	Weight (lb)	Elbow Height(in)	Forearm Length (in)	Full Arm Length (in)
1	R. H. Doolittle	35	5' 11"	165	44	17	23.5
2	P. D. Viana	31	5' 7"	137	41	11	21
3	J. O. House	32	6' 2"	195	47	13	25
4	C. Kromp	31	5' 7"	170	40.5	10.5	21.5
5	O. Bromberg	22	5' 11"	175	45	11.5	24
6	G. A. Grabowsky	20	5' 11"	190	46	12	23
7	E. G. Lindquist	39	5' 10"	175	44	11	24
8	J. Crim	21	6' 1"	205	46	12	23
9	H. T. Fichman	31	5' 11"	185	44	11	22.5
10	R. J. Wimmert	26	6' 0"	185	45	12	24

in front of the equipment at a distance equal to his forearm length and having his elbow at a height of 16.4 inches (the average lever size) above the shaft. In this way, the variation of the muscular pattern was very slight and all operators had the same position relative to the equipment (platforms of different heights were used to meet this need).

During the test, the operator had to move the lever between two mechanical stops performing a certain number of cycles during 8 seconds (this time interval was determined in several trial runs and judged sufficient to give a reasonable number of cycles). The choice of this type of motion[1] was established because it seemed to give a constant performance.

Before the run, the operator was instructed on the operation of the equipment, but due to the simplicity of the operation, he did not perform any trial run. The operator was told to operate at the maximum speed that he thought possible to maintain for 8 seconds. He had to grasp the lever by its upper end and start the motion from the left-hand stop. He was given three signals: a "stand-by" signal before each run; a "start" signal; and a "stop" signal. The time was recorded from the instant in which the lever left the left-hand stop until the "stop" signal.

1. For a discussion of hand motions, see Mundel, M. E., "A Study of Rhythm in Hand Motions", Iowa Studies in Engineering, Bulletin No. 12, p. 55.

Between runs a 3-minute rest pause was given. During that time the torque or the lever or both were changed following a randomized order of presentation (see Table 4, Appendix A). The purpose of the randomization was to decrease as much as possible the influence of that order upon the results (a table of random numbers was used to get the randomization[1]).

Each operator performed twenty-five runs using five levers to overcome five torques each. At the end of the runs, none showed signs of fatigue or reported it when asked.

The operators had no knowledge of their output during the experiment; thus, the possible influence of this knowledge upon the muscular work was not present[2].

In getting the results of the tests, a consistent procedure was adopted to interpret the record of each run which had been obtained with the kymograph. Since several trial runs indicated that the operator reached his maximum speed, in most cases, after the second cycle and maintained this speed during five to seven cycles and then began to slow down again, it was decided to measure, in each run, five consecutive cycles beginning with the third cycle. Due to

---

1. Arkin, H., and Colton, R. R., Tables for Statisticians, Barnes and Noble, Inc., New York, Table 23.

2. Wagner, Charles F., "The Effect of Knowledge of Output on Muscular Work", Jour. of Experimental Psychology, Vol. XVIII, No. 1, 1935, pp. 80-90.

the behavior of the ratchet lever, the cycle of operation consisted of two parts: during one part, the operator had to move the lever against the opposition of the frictional torque; during the other, the torque did not affect the operation, that is, the operator had practically no load to overcome. Only the loaded parts of the cycles were taken into consideration in the analysis of the results.

A scale of $\frac{1}{50}$ of one inch was used to measure the distance between two jogs in the kymograph record (Figure 3). This distance was proportional to the time spent by the operator to perform a semi-cycle; therefore, it was not necessary to convert the result into time. Also, the absolute values of the intervals of times themselves were unimportant, since the main concern was their relative values. Thus, only to plot the curves in Figures 4 and 5 were time values used. In all other cases, the distances obtained with the record given by the kymograph were used.

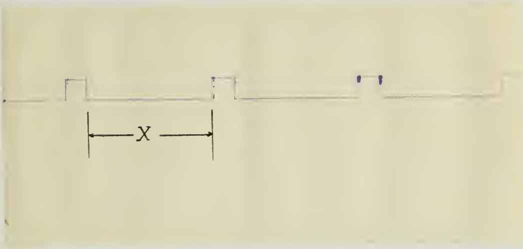

Figure 3

Sample of tape from Kymograph

RESULTS

The results for each combination of torque and lever are summarized and shown in Table 2.

Table 2

Average Lengths of Five Semi-Cycles for Each Combination of Torque and Lever

	Torque, In.-Lb.				
Lever	28	59	89	112	145
10	270.6	283.9	297.2	322.8	361.0
12	291.9	306.6	314.8	331.5	346.5
15	313.9	332.7	347.7	360.3	373.8
20	397.0	412.0	421.6	430.3	461.8
25	480.9	495.2	507.3	534.5	567.2

All numbers represent multiples of $\frac{1}{50}$ of one inch. As shown in Table 2, the 10-inch lever required the least time for all torques except 145 inch-pounds[1]; whereas, the 25-inch lever required the maximum time for all torques.

Table 5 (Appendix B) presents the results by operators for each combination of levers and torques. The analysis of variance was used to examine the data. The principal steps of this procedure are shown in Appendix C.

---

1. However, in Appendix D, it is shown that the minimum found with the 12-inch lever is not significant.

Two groups of curves were plotted using the data summarized in Table 3. Also, the best fitting curve was determined in each case by means of the method of least squares (see Appendix D).

Figure 4 shows the curves (both fitted and experimental) for

$t = f(l)$ for T = constant

Figure 5 shows the curves (both fitted and experimental) for

$t = F(T)$ for l = constant

where t = time required to perform five semi-cycles

l = length of the lever

T = torque

In order to use time values on the curves, the following was done:

The values in Table 2 were divided by 451.55, that is, by the speed of the kymograph paper expressed in fiftieths of one inch per second. Table 3 presents the values obtained which were used in the experimental curves.

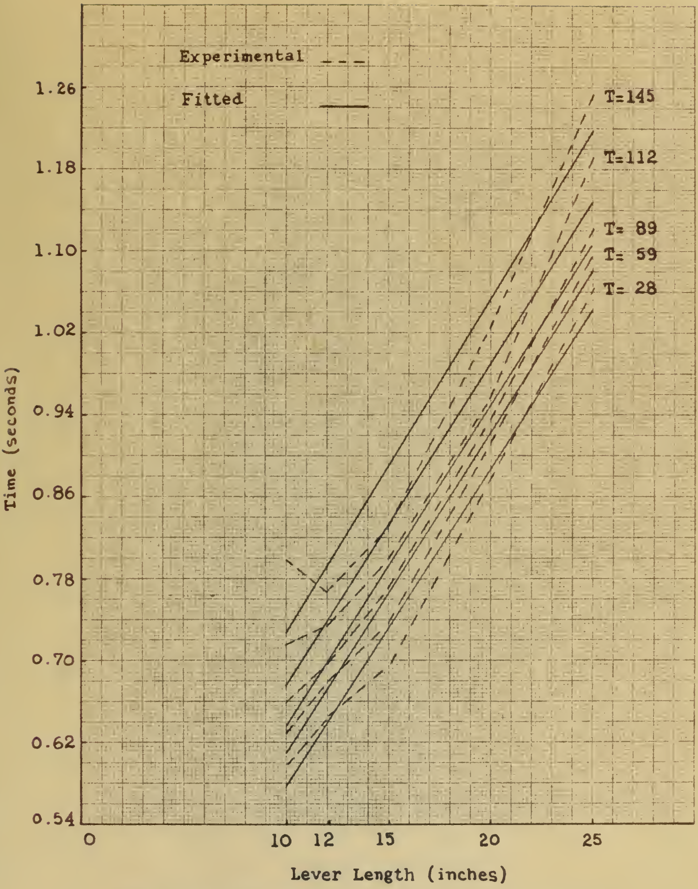

Fig. 4 - Curves for t = f(l) for T = constant

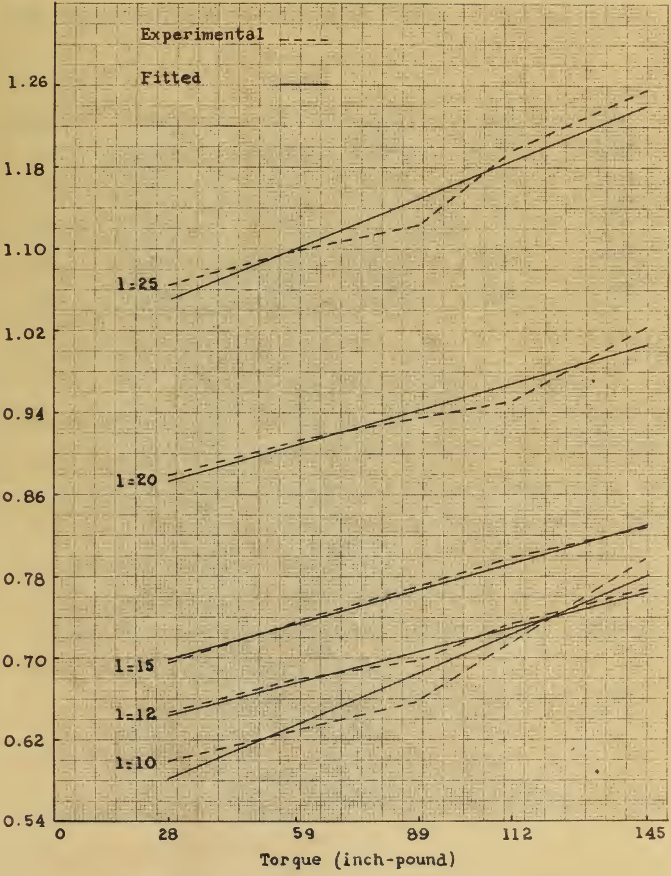

Fig. 5 — Curves for t = F(T) for 1 = constant

Table 3

Average duration, in seconds, of five semi-cycles for each combination of torque and lever.

			Torque		
Lever	28	59	89	112	145
10	0.599	0.629	0.658	0.715	0.799
12	0.646	0.679	0.697	0.734	0.767
15	0.695	0.736	0.770	0.798	0.828
20	0.879	0.912	0.934	0.953	1.023
25	1.065	1.097	1.123	1.194	1.256

DISCUSSION OF RESULTS

As mentioned before, the data were analyzed statistically by using an analysis of variance procedure. The results of this analysis are summarized in Table 6 of Appendix B.

The variance for torques, levers and individuals, respectively, Q_T, Q_l and Q_i, came out strongly significant. In Figures 4 and 5 we can easily detect the apparent influence of the variation among torques and levers.

The so-called interactions, that is, Q_{Tl}, Q_{Ti} and Q_{Til}, though still significant, are in much less degree and thus reveal a much less marked influence. Among these interactions, that concerned with levers versus individuals is the most highly significant. This indicates that, at least for this group of operators and set of levers, the variation of lever size affected the operation in different ways, though the results as a whole show a common and general trend. The interaction concerning torques versus individuals versus levers shows the least degree of significance and thus helps explain the kind of general result found, that is, a reasonable agreement among performances.

Let us examine now the curves of Figure 4. They are the lines

$$t = f(l) \qquad \text{for } T = \text{constant}$$

Since the straight lines were the best fitting curves, we see

that there was a close proportionality among the lengths of the levers and the times required to operate. Because of the proportionality which exists between the lever size and the path that the hand of the operator had to follow, the previous statement amounts to saying that the time required to operate the lever was strongly dependent on the path that the hand followed. Probably, this was the dominant factor affecting the time.

The fitted curves show that the 10-inch lever required the least time to operate under all torques; however, no conclusion can be drawn for sizes smaller than 10 inches.

Let us examine now the curves of Figure 5. They are the lines

$$t = F(T) \quad \text{for } l = \text{constant}$$

Since straight lines were the best fitting curves, it is apparent that there is close proportionality among the times and the torques.

CONCLUSIONS

Under the conditions of the experiment and for the group of operators who performed the tests, the following conclusions may be drawn:

(a) When the torque increases and the lever size is kept constant, the time required to operate increases closely proportional to the torque.

(b) The time required to operate is closely proportional to the distance that the hand has to travel.

(c) The path that the hand has to travel is, probably, the predominant factor determining the time for operation.

(d) The 10-inch lever requires the minimum time for operation and the 25-inch lever requires the maximum time for operation.

APPENDIX A

Tables 4a to 4j-- Order of Presentation

These tables present the randomized order of presentation for each subject.

The conventions used in Table 5 (Appendix B) were also adopted here.

4a -- Subject No. 1

Lever No.	Run No. Torque No.				
5	1 1	2 5	3 4	4 3	5 2
2	6 3	7 1	8 5	9 2	10 4
3	11 2	12 3	13 5	14 4	15 1
4	16 4	17 2	18 3	19 5	20 1
1	21 3	22 4	23 5	24 1	25 2

4b - Subject No. 2

Lever No.	Run No. Torque No.				
2	26 5	27 3	28 1	29 4	30 2
1	31 4	32 5	33 1	34 3	35 2
3	36 2	37 3	38 5	39 4	40 1
4	41 3	42 1	43 4	44 2	45 5
5	46 1	47 4	48 5	49 2	50 3

4c - Subject No. 3

Lever No.	Run No. Torque No.				
3	51 1	52 5	53 4	54 3	55 2
5	56 3	57 4	58 2	59 5	60 1
1	61 5	62 1	63 3	64 2	65 4
2	66 2	67 4	68 5	69 1	70 3
4	71 4	72 1	73 5	74 3	75 2

4d - Subject No. 4

Lever No.	Run No. Torque No.				
2	76 2	77 4	78 1	79 5	80 3
3	81 4	82 1	83 5	84 3	85 2
5	86 5	87 2	88 1	89 3	90 4
4	91 3	92 1	93 4	94 2	95 5
	96	97	98	99	100

4e - Subject No. 5

Lever No.	Run No.	Torque No.	Run No.	Torque No.	Run No.	Torque No.	Run No.	Torque No.	Run No.	Torque No.
5	101	4	102	5	103	2	104	1	105	3
4	106	5	107	1	108	3	109	4	110	2
3	111	3	112	5	113	4	114	2	115	1
2	116	2	117	5	118	1	119	3	120	4
1	121	1	122	5	123	3	124	2	125	4

4f - Subject No. 6

Lever No.	Run No.	Torque No.	Run No.	Torque No.	Run No.	Torque No.	Run No.	Torque No.	Run No.	Torque No.
4	126	4	127	2	128	5	129	1	130	3
3	131	5	132	2	133	4	134	3	135	1
1	136	3	137	4	138	5	139	1	140	2
2	141	2	142	3	143	5	144	4	145	1
5	146	1	147	4	148	5	149	2	150	3

4g - Subject No. 7

Lever No.	Run No.	Torque No.	Run No.	Torque No.	Run No.	Torque No.	Run No.	Torque No.	Run No.	Torque No.
1	151	5	152	2	153	3	154	4	155	1
4	156	2	157	4	158	1	159	3	160	5
5	161	4	162	2	163	3	164	5	165	1
2	166	3	167	2	168	1	169	5	170	4
3	171	1	172	5	173	2	174	4	175	3

4h - Subject No. 8

Lever No.	Run No. Torque No.				
1	176 2	177 3	178 1	179 4	180 5
5	181 4	182 3	183 3	184 5	185 1
4	186 3	187 4	188 1	189 2	190 5
2	191 5	192 3	193 1	194 2	195 4
3	196 1	197 4	198 5	199 2	200 3

4i - Subject No. 9

Lever No.	Run No. Torque No.				
3	201 2	202 3	203 1	204 4	205 5
5	206 5	207 4	208 1	209 3	210 2
4	211 1	212 3	213 5	214 2	215 4
1	216 3	217 5	218 4	219 2	220 1
2	221 4	222 2	223 5	224 1	225 3

4j - Subject No. 10

Lever No.	Run No. Torque No.				
4	226 3	227 2	228 5	229 4	230 1
2	231 4	232 3	233 2	234 1	235 5
3	236 2	237 3	238 1	239 4	240 5
1	241 5	242 2	243 1	244 3	245 4
5	246 1	247 4	248 5	249 2	250 3

APPENDIX B

Tables 5a to 5j -- Results by Operators

These tables present the results obtained for each operator and each combination of torques and levers, in the five measured semi-cycles. They also give the totals of these five semi-cycles. The numbers express fiftieths of one inch. The following convention was adopted to write the tables:

Lever No.	Length	Torque No.	Value
I	10	1	28
II	12	2	59
III	15	3	89
IV	20	4	112
V	25	5	145

Table 5a

Subject No. 1

Lever	Torque	X_1	X_2	X_3	X_4	X_5	ΣX
I	1	49	48	43	45	41	226
	2	44	52	46	49	45	236
	3	48	49	41	49	49	236
	4	50	53	48	43	45	239
	5	69	72	64	63	65	333
II	1	51	53	52	52	51	259
	2	55	56	52	52	56	271
	3	53	57	53	56	59	278
	4	55	61	63	55	57	291
	5	56	60	57	59	59	291
III	1	57	55	57	52	55	276
	2	52	59	57	56	55	279
	3	65	58	56	53	55	287
	4	64	63	67	61	67	322
	5	79	69	68	67	67	350
IV	1	64	62	59	65	63	313
	2	64	65	62	65	70	326
	3	65	60	68	65	68	326
	4	60	60	69	73	65	327
	5	67	63	66	68	64	328
V	1	88	81	87	86	87	429
	2	84	85	88	85	91	433
	3	95	92	84	102	101	474
	4	93	98	100	98	102	491
	5	97	127	95	99	120	538

Table 5b

Subject No. 2

Lever	Torque	X_1	X_2	X_3	X_4	X_5	ΣX
I	1	62	69	61	63	68	323
	2	60	69	69	62	65	325
	3	69	78	78	75	69	369
	4	85	83	74	89	82	413
	5	84	84	92	86	88	434
II	1	73	67	72	76	72	360
	2	73	73	73	74	75	368
	3	85	78	76	73	73	385
	4	76	85	83	79	80	403
	5	98	79	90	83	80	430
III	1	71	69	75	69	79	363
	2	83	82	77	81	84	407
	3	84	92	84	80	84	424
	4	85	84	79	89	88	425
	5	96	98	95	90	83	462
IV	1	96	98	95	95	96	480
	2	103	103	101	95	95	497
	3	96	101	104	130	98	529
	4	106	103	107	105	110	531
	5	109	112	107	123	116	567
V	1	115	121	116	120	109	581
	2	121	115	118	115	111	580
	3	119	119	123	123	131	615
	4	130	123	129	134	117	633
	5	144	141	138	131	130	684

Table 5c

Subject No. 3

Lever	Torque	X_1	X_2	X_3	X_4	X_5	ΣX
I	1	49	46	50	45	49	239
	2	53	51	53	50	54	261
	3	54	53	52	52	59	270
	4	53	58	58	54	58	281
	5	65	61	60	53	58	297
II	1	54	55	52	52	49	262
	2	60	56	56	57	53	282
	3	53	56	56	54	58	277
	4	53	56	60	56	60	285
	5	57	57	56	52	57	279
III	1	54	54	52	55	53	268
	2	53	55	58	56	52	274
	3	57	57	60	57	56	287
	4	60	62	62	62	65	311
	5	65	69	68	65	68	335
IV	1	74	72	70	72	68	356
	2	78	69	78	81	80	386
	3	76	81	79	72	76	384
	4	68	76	79	83	78	384
	5	85	84	92	100	84	445
V	1	90	88	85	84	88	435
	2	84	91	91	86	91	443
	3	84	95	88	87	92	446
	4	99	87	90	89	94	459
	5	89	93	120	92	100	494

Table 5d

Subject No. 4

Lever	Torque	X_1	X_2	X_3	X_4	X_5	ΣX
I	1	59	51	53	53	56	272
	2	53	57	53	60	61	284
	3	60	57	61	58	61	297
	4	62	63	61	57	65	308
	5	68	65	64	64	72	333
II	1	58	53	59	56	58	284
	2	59	60	60	62	61	302
	3	64	61	61	63	55	304
	4	63	64	63	68	63	321
	5	65	60	64	67	65	321
III	1	57	57	54	57	61	286
	2	60	62	53	56	59	290
	3	63	65	62	63	60	313
	4	63	61	64	64	70	322
	5	76	65	68	70	68	347
IV	1	81	77	80	78	77	393
	2	83	80	76	78	82	399
	3	81	85	75	86	81	408
	4	90	83	81	78	88	420
	5	92	100	79	88	85	444
V	1	104	95	100	98	91	488
	2	100	96	99	104	104	503
	3	97	108	100	107	105	517
	4	100	112	106	104	108	530
	5	115	107	101	107	113	543

Table 5e

Subject No. 5

Lever	Torque	X_1	X_2	X_3	X_4	X_5	ΣX
I	1	49	41	43	44	44	221
	2	45	48	48	39	43	223
	3	46	46	49	47	47	235
	4	53	53	53	53	43	255
	5	65	64	64	55	55	303
II	1	48	54	49	47	46	244
	2	48	52	45	49	54	248
	3	52	52	53	54	50	261
	4	57	53	60	56	53	279
	5	64	60	60	52	55	291
III	1	52	54	54	55	51	266
	2	57	54	53	53	56	273
	3	52	59	60	60	60	291
	4	70	59	58	61	60	308
	5	64	62	61	60	61	308
IV	1	54	63	63	74	74	328
	2	67	64	68	67	66	332
	3	73	68	64	68	68	341
	4	71	73	68	67	67	346
	5	82	91	82	79	81	415
V	1	83	84	90	79	77	413
	2	96	99	99	92	95	481
	3	98	83	97	116	98	492
	4	100	98	101	127	87	513
	5	142	99	100	99	97	537

Table 5f

Subject No. 6

Lever	Torque	X_1	X_2	X_3	X_4	X_5	ΣX
I	1	62	65	69	68	60	324
	2	64	63	69	68	68	332
	3	70	69	62	62	73	336
	4	67	67	66	73	67	340
	5	69	69	76	72	67	353
II	1	68	71	66	56	70	331
	2	65	67	65	68	68	333
	3	73	64	68	69	75	349
	4	69	68	69	71	75	352
	5	73	71	69	73	66	352
III	1	74	77	69	70	71	361
	2	69	77	81	74	73	374
	3	87	75	70	73	71	376
	4	68	77	78	81	83	387
	5	73	75	90	77	73	388
IV	1	91	86	92	105	93	467
	2	91	86	91	96	105	469
	3	105	93	97	88	93	476
	4	116	96	100	98	99	509
	5	125	113	112	111	105	566
V	1	144	109	98	101	109	561
	2	107	115	114	108	121	565
	3	117	112	119	113	112	573
	4	115	120	116	113	113	577
	5	112	112	118	120	116	578

Table 5g

Subject No. 7

Lever	Torque	X_1	X_2	X_3	X_4	X_5	ΣX
I	1	49	44	46	49	49	237
	2	68	57	53	53	57	288
	3	69	69	61	53	49	301
	4	69	64	63	54	56	306
	5	74	67	79	74	78	372
II	1	64	53	51	49	50	267
	2	53	58	57	62	65	295
	3	65	61	62	65	54	307
	4	69	69	70	63	73	344
	5	77	67	74	70	70	358
III	1	67	70	67	63	60	327
	2	79	76	79	86	80	400
	3	95	99	82	84	88	448
	4	87	80	81	81	81	410
	5	71	83	88	75	92	409
IV	1	73	70	67	67	67	344
	2	80	77	83	75	83	398
	3	84	82	81	81	80	408
	4	95	91	93	69	76	424
	5	96	96	79	81	91	443
V	1	106	81	85	75	72	419
	2	94	76	95	92	103	460
	3	108	89	87	87	87	458
	4	96	98	108	108	112	522
	5	134	119	88	105	107	553

Table 5h

Subject No. 8

Lever	Torque	X_1	X_2	X_3	X_4	X_5	ΣX
I	1	68	73	69	79	65	354
	2	73	73	78	72	70	366
	3	75	76	77	71	69	368
	4	92	100	96	88	102	478
	5	104	108	96	94	97	499
II	1	63	58	65	72	67	323
	2	69	66	71	56	65	327
	3	65	70	68	65	68	338
	4	73	77	76	77	69	372
	5	80	72	78	77	80	387
III	1	64	72	70	73	70	349
	2	70	70	72	72	70	354
	3	71	68	75	75	68	357
	4	70	70	72	73	73	358
	5	76	76	73	73	73	371
IV	1	77	81	76	84	80	398
	2	80	81	86	83	80	410
	3	86	85	86	85	86	428
	4	82	85	91	92	84	434
	5	96	88	84	85	89	442
V	1	96	93	107	99	93	488
	2	102	101	103	107	105	518
	3	109	112	104	101	94	520
	4	114	108	103	117	105	547
	5	111	127	121	126	116	601

Table 5i

Subject No. 9

Lever	Torque	X_1	X_2	X_3	X_4	X_5	ΣX
I	1	52	50	49	43	45	244
	2	53	46	49	50	46	244
	3	54	53	46	46	45	244
	4	62	64	59	56	58	299
	5	92	77	72	66	67	374
II	1	53	58	58	54	50	273
	2	69	63	64	65	63	324
	3	62	64	70	68	66	330
	4	70	68	63	70	65	336
	5	93	88	80	70	65	396
III	1	69	70	69	62	59	329
	2	73	70	74	74	70	361
	3	81	77	76	70	77	381
	4	84	89	79	80	89	421
	5	80	84	84	89	86	423
IV	1	90	99	97	99	96	481
	2	100	103	102	94	91	490
	3	104	104	104	96	90	498
	4	105	106	101	98	100	510
	5	113	110	107	105	96	531
V	1	112	113	103	108	112	548
	2	115	104	115	108	120	562
	3	121	108	112	112	116	569
	4	126	131	130	121	122	630
	5	146	139	140	140	139	704

Table 5j

Subject No. 10

Lever	Torque	X_1	X_2	X_3	X_4	X_5	ΣX
I	1	51	53	55	50	57	266
	2	58	50	58	57	57	280
	3	58	61	62	65	70	316
	4	63	62	62	65	57	309
	5	62	57	61	67	65	312
II	1	62	59	65	66	62	314
	2	65	63	61	62	65	316
	3	62	63	64	69	63	321
	4	65	64	66	71	66	332
	5	62	71	70	80	77	360
III	1	61	61	65	65	62	314
	2	58	66	65	65	61	315
	3	64	61	61	63	64	313
	4	71	66	65	67	70	339
	5	67	62	73	70	73	345
IV	1	80	81	81	85	83	410
	2	80	88	87	81	77	413
	3	83	72	84	89	90	418
	4	86	83	72	89	88	418
	5	91	89	94	81	82	437
V	1	88	87	92	88	92	447
	2	77	78	85	80	87	407
	3	77	82	80	82	88	409
	4	88	96	88	88	83	443
	5	92	84	86	89	89	440

APPENDIX C

Analysis of Variance

The following steps were observed:

1. Computation of the within-cell variation --

$$\sum_{1}^{250}\left(\sum_{1}^{5}X^2\right) - \frac{\sum_{1}^{250}\left(\sum_{1}^{5}X\right)^2}{5}$$

where X = each single measurement in a cell; that is, a series of five results corresponding to a combination of lever and torque for one operator.

Within-cell variation = 7825974 - 7803399.2 = 22574.8

2. Computation of average measurement error --

$$\text{Average measurement error} = \frac{22574.8}{1250-250} = 22.5748$$

3. Computation of variation among torques (Q_T) -

$$Q_T = \frac{T_1^2 + T_2^2 + T_3^2 + T_4^2 + T_5^2}{250} - \frac{T^2}{1250}$$

where T_1 = total of all totals for torque 1

T_2 = total of all totals for torque 2, etc.

T = grand total of these.

$$Q_T = \frac{1836613306}{250} - \frac{9145096900}{1250}$$

Q_T = 30375.704

4. Computation of variation among levers (Q_l) --

$$Q_l = \frac{T_I^2 + T_{II}^2 + T_{III}^2 + T_{IV}^2 + T_V^2}{250} - \frac{T^2}{1250}$$

where T_I = total of all totals for lever I, etc.

T = grand total of these.

$$Q_l = \frac{1906595980}{250} - \frac{9145096900}{1250} = 310306.4$$

5. Computation of variation among individuals (Q_i) --

$$Q_i = \frac{T_a^2 + T_b^2 + \dots + T_j^2}{125} - \frac{T^2}{1250}$$

where T_a = total of all totals for individual a, etc.

T = grand total of these.

$$Q_i = \frac{926826136}{125} - \frac{9145096900}{1250} = 98531.568$$

6. Computation of variation for torques versus levers (Q_{Tl}) --

$$Q_{Tl} = \frac{T_{1I}^2 + T_{1II}^2 + \dots + T_{1V}^2 + T_{2I}^2 + \dots + T_{5V}^2}{50} - \frac{T^2}{1250} -$$

$$- Q_T - Q_l$$

where T_{1I} = total of totals of individuals for torque 1 and lever I, etc.

T = grand total of these.

$$Q_{Tl} = \frac{382935940}{50} - \frac{9145096900}{1250} - 30375.704 - 310306.4 =$$

$$= 1959.176$$

7. Computation of variation for torques versus individuals (Q_{Ti}) --

$$Q_{Ti} = \frac{T_{1a}^2 + \dots + T_{1j}^2 + T_{2a}^2 + \dots + T_{5j}^2}{25} - \frac{T^2}{1250} - Q_T - Q_i$$

where T_{1a} = total of totals for torque 1 and individual a for all levers, etc.

T = grand total of these.

$$Q_{Ti} = \frac{186232615}{25} - \frac{9145096900}{1250} - 30375.704 - 98531.568$$

$$= 4319.808$$

8. Computation of variation for levers versus individuals (Q_{li}) --

$$Q_{li} = \frac{T_{Ia}^{2} + \cdots + T_{Ij}^{2} + \cdots + T_{Vj}^{2}}{25} - \frac{T^2}{1250} - Q_l - Q_i$$

where T_{Ia} = total of totals of individual a and lever I for all torques, etc.

T = grand total of these.

$$Q_{li} = \frac{193957344}{25} - \frac{9145096900}{1250} - 310306.4 - 98531.568$$

$$= 33390.28$$

9. Computation of variation for torques versus individuals versus levers (Q_{Til}) --

$$Q_{Til} = \frac{\text{Sum of squares of sums for each individual on one torque and one lever}}{5}$$

$$- \frac{T^2}{1250} - Q_T - Q_l - Q_i - Q_{Tl} - Q_{Ti} - Q_{li}$$

$$Q_{Til} = \frac{39016976}{5} - \frac{9145096900}{1250} - 30375.754 - 310306.4$$

$$- 98531.568 - 1959.176 - 4319.808 - 33390.28$$

$$= 6434.744$$

10. Computation of F's for each variation and test of significance.

The results are shown in Table 6 which follows.

Table 6

General Results of the Analysis of Variance

Quantity	Value	D.F.	Mean Square	F	Significance
Q_T	30375.704	4	7593.926	336.389	*
Q_l	310306.400	4	77576.600	3436.424	*
Q_i	98531.568	9	10947.952	484.963	*
Q_{Tl}	1959.176	16	122.448	5.424	*
Q_{Ti}	4319.808	36	119.946	5.313	*
Q_{li}	33390.280	36	927.507	41.086	*
Q_{Til}	8434.744	144	58.575	2.595	*
Error	22574.800	1000	22.575		

* - means: significant value.

Table 7

Limits for Levels 5% and 1%

Level \ D.F.	4	9	16	36	144
5%	2.38	1.89	1.65	1.43	1.23
1%	3.34	2.43	2.01	1.57	1.33

Table gives levels for D.F. shown versus D.F. = 1000.

APPENDIX D

Determination of the best representative curves of the results of the experiment.

The method of the least squares was adopted and the following equations used to determine the parameters of the straight lines $Y = a + bX$:

$$a = \frac{(\Sigma Y)(\Sigma X^2) - (\Sigma X)(\Sigma XY)}{N\Sigma X^2 - (\Sigma X)^2}$$

$$b = \frac{N\Sigma XY - (\Sigma X)(\Sigma Y)}{N\Sigma X^2 - (\Sigma X)^2}$$

The results found for the two groups of curves are presented in Table 8 and Table 9. It was found by use of the appropriate test that departure from linearity is not significant for the curves $t = f(l)$ and $t = F(T)$.

Table 8

Slopes and intercepts for the best fitting straight lines for t = f(l) for T = constant.

T	28	59	89	112	145
a	0.2635	0.2970	0.3235	0.3612	0.4035
b	0.03129	0.03131	0.03125	0.03140	0.03238

Table 9

Slopes and intercepts for the best fitting straight lines for t = f(l) for l = constant.

l	10	12	15	20	25
a	0.5337	0.6154	0.6670	0.8409	1.0039
b	0.001690	0.001031	0.001137	0.001146	0.001628

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